Star Formation in an Unexpected Place: Early-type Galaxies

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ABSTRACT

Many early-type galaxies are detected at 24 to 160μm but the emission is usually dominated by an AGN or heating from the evolved stellar population. Here we present MIPS observations of a sample of elliptical and lenticular galaxies which are rich in cold molecular gas, and we investigate how much of the MIR to FIR emission could be due to star formation activity. The 24μm images show a rich variety of structures, including nuclear point sources, rings, disks, and smooth extended emission, and comparisons to matched-resolution CO and radio continuum images suggest that the bulk of the 24μm emission could be traced to star formation. The star formation efficiencies are comparable to those found in normal spirals. Some future directions for progress are also mentioned.

Subject headings: galaxies: ISM — infrared: galaxies — infrared: ISM — ISM: dust, extinction — ISM: structure — galaxies: elliptical and lenticular, cD

1. Introduction

In recent years, UV and optical photometry and spectroscopy of nearby elliptical galaxies has suggested that these galaxies, which have a reputation for being old, red, and dead, may not be quite as dead as previously assumed. Some 15% to 30% of local ellipticals seem to be experiencing small amounts of present day star formation activity (Schawinski et al. 2007a, 2007b; Kaviraj et al. 2007). The star formation is not intense enough to cause serious problems for the galaxies' morphological classification, as it only amounts to a few percent of the total stellar mass. However, this current day disk growth inside spheroidal galaxies may be a faint remnant of a process which was more vigorous in the past and may have played a role in establishing the spectrum of galaxy morphologies we observe today.

Star formation of course requires cold gas, so interpreting the UV and optical data in terms of star formation activity has important implications both for the early-type galaxies

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and for a general understanding of the star formation process. It is not obvious that star formation should "work" the same way inside spheroidal galaxies as it does inside disks, with the same efficiency or the same dependence on the gas surface density. For example, it has been hypothesized that even if there is a molecular disk inside an elliptical or lenticular galaxy, the disk would probably be stabilized by the galaxy's steep gravitational potential (e.g. Kennicutt 1989; Okuda et al. 2005; Kawata et al. 2007). Thus it is of interest to probe the relationships between molecular gas and star formation activity in early-type galaxies.

It is not as straightforward to measure star formation rates in early-type galaxies as it is in spirals, however. Optical line emission is common in ellipticals (Shields 1991; Goudfrooij et al. 1994; Sarzi et al. 2006), but usually its widespread and/or filamentary distribution and its line ratios indicate that it is more closely related to AGN activity or to cooling from hot gas than to star formation. Far-IR and cm-wave radio continuum emission are also commonly used as tracers of star formation activity in gas-rich spirals, but the mid-IR and far-IR emission in ellipticals is usually attributed to AGN activity and/or the evolved stellar population rather than to star formation (Temi et al. 2007, 2008). Here we investigate some evidence for and against star formation activity in a sample of elliptical and lenticular galaxies that have unusually large molecular gas contents (Table 1). We make use of matched-resolution images of the molecular gas distribution, the cm-wave radio continuum and the 24μm intensity.

2.   Molecular Gas in Early-type Galaxies

Early surveys for molecular gas in early-type galaxies were strongly biased towards FIR-bright targets, but more recent work is not biased in this way and still finds significant molecular gas contents. Welch & Sage (2003) found a surprisingly high CO detection rate of 78% in a volume-limited sample of nearby field lenticular galaxies, and Sage et al. (2007) detected CO emission in 33% of a similar sample of field ellipticals. Combes et al. (2007) also detected CO emission in 28% of the early-type galaxies in the SAURON survey (de Zeeuw et al. 2002), a representative sample which uniformly fills an optical magnitude – apparent axis ratio space. Thus, the CO detection rates may be high enough to support the UV-inferred incidence of star formation activity. The cold gas masses are highly variable in these detections, with M_{gas}/L_B in the range 10^{-1} to 10^{-3} and lower.

Since we are interested in morphology as a means of distinguishing the origin of the radio and IR emission, we have selected for this project elliptical and lenticular galaxies with maps resolving their molecular gas distribution. If the 24μm emission arises in star formation activity, we expect it to trace the molecular gas. If the 24μm emission is related

to an AGN we expect it to be a point source, and if it is circumstellar dust it should trace the stellar distribution. Thus, we also required the targets to have molecular gas which is extended enough that it should be resolved in the 24μm images. The molecular gas maps are published by Young (2002, 2005) and Young, Bureau, & Cappellari (2008); 1.4 GHz (20cm) radio continuum maps are available from the VLA FIRST survey and from Lucero & Young (2007).

3. Comparison samples: CO-poor early-type galaxies

A handful of elliptical and lenticular galaxies were observed as part of the SINGS survey and their morphologies are discussed by Bendo et al. (2007). With a couple of exceptions, such as NGC 1316 (which contains an extended arc of emission) and NGC 5866 (which contains an edge-on disk), these early-type galaxies tended to have highly compact, symmetric nuclear pointlike or nearly-point sources at 24μm. At least three of these are detected in CO emission but CO maps are not yet available.

MIPS observations of elliptical galaxies have also been published by Temi et al. (2007, 2008) and Kaneda et al. (2007). Of the 19 galaxies discussed by Temi et al. (2008), 13 have been searched for CO emission and none have been detected. In these works the 24μm emission from the ellipticals follows the near-IR surface brightness profiles very closely, so the 24μm surface brightness is close to a $r^{1/4}$ profile with the same effective radius as in the K-band. In addition, Temi et al. (2007) have shown that the 24μm emission globally tracks the optical luminosity in elliptical galaxies as there is a tight linear correlation between the 24μm flux density and the B-band flux density. This 24μm emission is interpreted to be circumstellar dust from the mass loss of post main sequence stars. Thus, in the majority of the elliptical galaxies that are not CO-rich the 24μm emission seems to either follow the stellar photospheric emission or a nuclear source.

4. Results: 24μm morphologies

Simple model fits are made in order to provide some parametrization of the 24 μm morphologies. We first constructed an empirical PSF from archival observations of 3C 273, 3C 279, and BL Lac. Point sources, exponential disks, rings, and de Vaucouleurs $r^{1/4}$ profiles (and combinations of these) are convolved with the PSF and fit to the images, just as was done for the Sombrero Galaxy by Bendo et al. (2006). None of the CO-rich early-type galaxies are pure point sources at 24μm; all are resolved, but are still significantly less extended than

the stellar distributions in the NIR and optical.

The 24μm intensity is a function of both the dust surface density and the illuminating radiation field. Possible dust heating sources include the post-main sequence stellar population, star formation regions, and AGN. Thus, the 24μm emission by itself may not necessarily indicate the presence of star formation. However, star formation is expected to be accompanied by spatially resolved cm-wave radio continuum emission (Condon 1992), whereas dust heated by the radiation from evolved stars would not be. Therefore the comparisons with the distribution of the molecular gas (the raw material for star formation) and the radio continuum provide constraints on the origin of the 24μm emission.

Figures 1 and 2 show some of the variety of morphologies in these CO-rich early-type galaxies. For example, UGC 1503 shows a regularly rotating molecular gas (and dust) disk of diameter $30'' = 9.7$ kpc, with a similarly sized ring of radio continuum emission. The 24μm emission also shows a ring with a central dip, and both radio continuum and 24μm have morphologies consistent with star formation in the molecular gas. Most of the other cases in the sample also have closely matching radio, 24μm and CO morphologies, and they are interpreted in a similar manner.

In the case of NGC 2320 it is not at all clear whether the 24μm emission is driven by star formation. The galaxy's radio continuum emission is more likely due to AGN activity than to star formation (Young 2005). The 24μm emission is well fit by a smooth $r^{1/4}$ model with half-light semimajor and semiminor axes of $4'' \times 2''$, but this is five times smaller than the effective radius of the stellar distribution. This modestly extended 24μm emission certainly could be driven by star formation in the inner part of the molecular gas disk, but star formation activity is not required.

5. IR luminosities and star formation efficiencies

Figure 3 compares the 24μm and optical luminosities of CO-rich and CO-poor early-type galaxies. The ones rich in molecular gas are typically a factor of 10 more luminous at 24μm, for a given optical luminosity, than would be expected if their 24μm emission were entirely circumstellar in origin. Our morphological analysis has also shown that the 24μm morphology is not that of point sources and is a much better match to the molecular gas distributions than to the stellar light profiles. In addition, Figure 3 shows that the FIR/radio continuum flux density ratios are (with the exception of NGC 2320) consistent with star formation activity. Based on this evidence we believe it is reasonable to attribute the bulk of the 24μm emission in the CO-rich early-type galaxies to star formation. Under the assumption
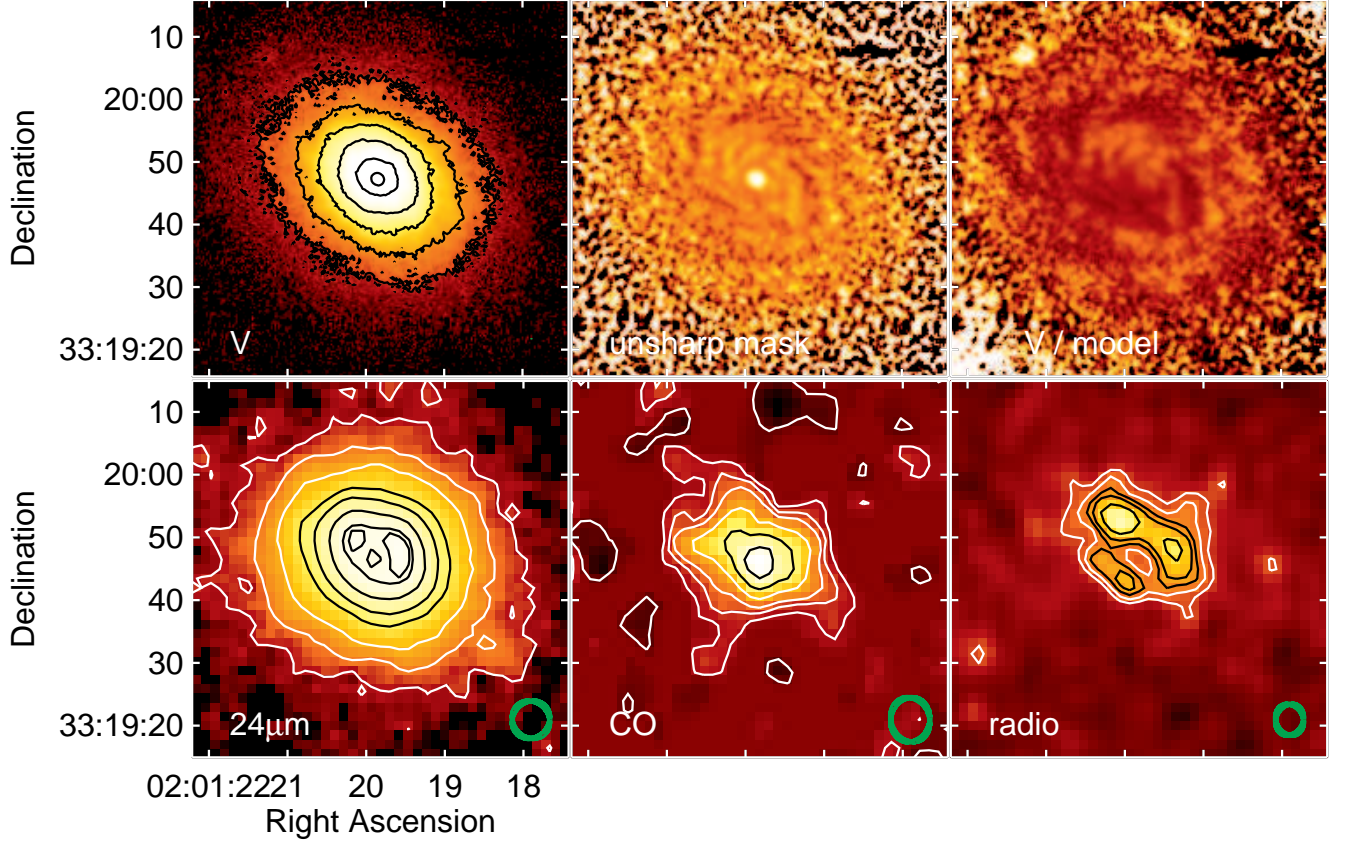
Fig. 1.— Optical, IR, CO and radio continuum morphology of UGC 1503. Optical contours are spaced by a factor of two. The top row, center panel is an unsharp-masked V image and the left panel is the ratio of the V to a smooth Multi-Gaussian Expansion model (Cappellari 2002). Contour levels in the 24μm image are 2, 5, 10, 20, 30, 50, 70, and 75 percent of the peak (6.1 MJy sr^{-1}). Contour levels in the CO image are -10, 10, 20, 30, 50, 70, and 90 percent of the peak (6.3 Jy bm^{-1} km s^{-1}). Contours in the 1.4 GHz radio continuum image are 0.09, 0.12, 0.15, 0.18, and 0.24 mJy bm^{-1}. Green circles show the spatial resolution.
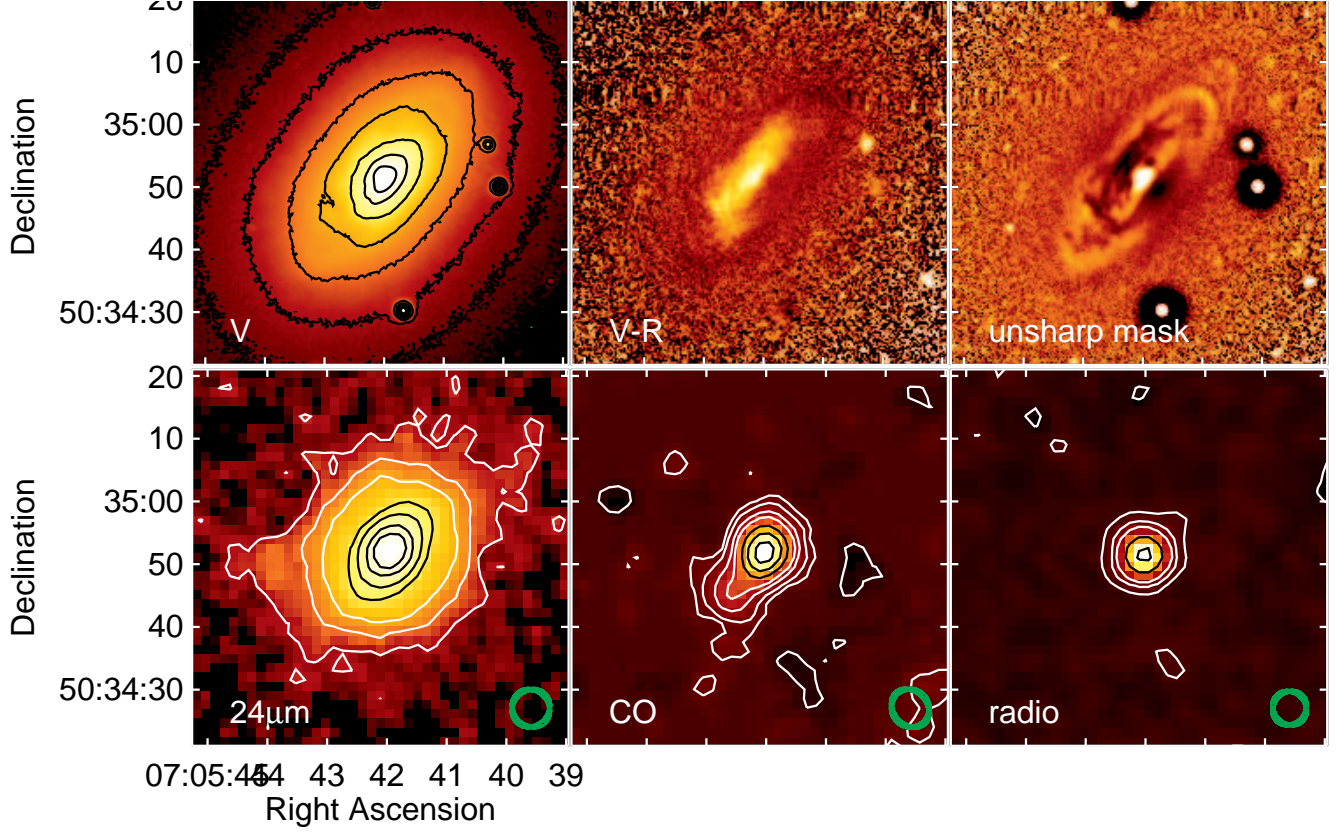
Fig. 2.— Optical, IR, CO and radio continuum morphology of NGC 2320. Optical contours are spaced by a factor of two. Contours in the 24μm image are 2, 5, 10, 20, 30, 50, 70, and 90 percent of the peak (5.6 MJy sr^{-1}). Contours in the CO image are -5, 5, 10, 20, 30, 50, 70, and 90 percent of the peak (29.1 Jy bm^{-1} km s^{-1}). Contours in the 1.4 GHz radio continuum image are -3, 3, 10, 20, 50, and 90 percent of the peak (13.1 mJy bm^{-1}). Green circles show the beam sizes (FWHM).

Table 1.   Sample Galaxies – Basic Properties

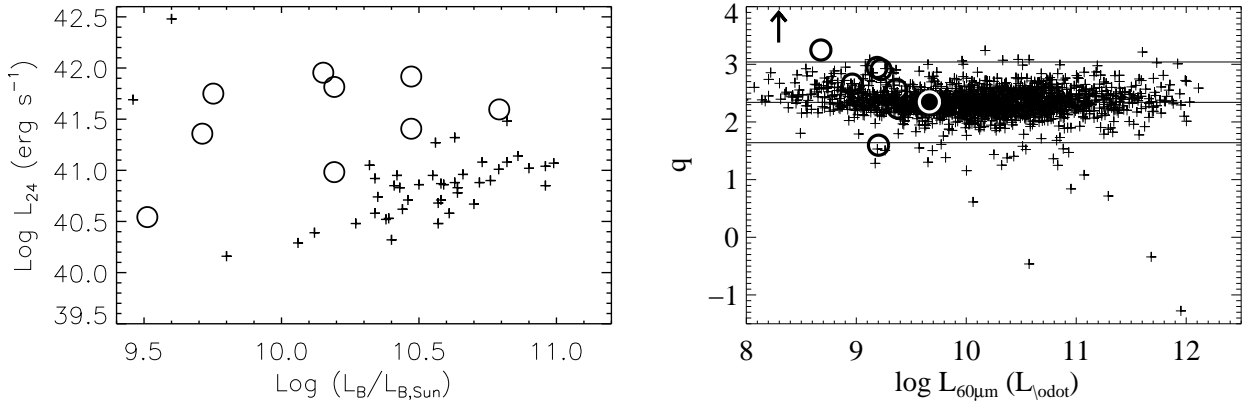| Name	Type	Dist (Mpc)	log L_B ($L_\odot$)	log $L_{60\mu m}$ ($L_{B,\odot}$)	$M(H_2)$ 10^8 $M_\odot$	environment
UGC 1503	E	67	10.2	9.4	25	field
NGC 0807	E	63	10.5	9.2	19	field
NGC 2320	E	77	10.8	9.2	43	group dominant
NGC 3032	S0	21	9.7	9.0	5.0	field
NGC 3656	I0	42	10.2	9.7	64	merger remnant
NGC 4459	S0	16	10.2	8.7	1.6	Virgo Cluster
NGC 4476	E/S0	17	9.5	8.3	1.5	Virgo Cluster
NGC 4526	S0	16	10.5	9.2	5.7	Virgo Cluster
NGC 5666	Ec/S?	34	9.8	9.4	7.8	field

Fig. 3.— (Left) Comparison of the $24\mu m$ luminosity and optical luminosity for the CO-rich early-type galaxies (circles) and the generally CO-poor ellipticals of Temi, Brighenti, & Mathews 2008 (crosses). (Right) FIR-to-radio flux ratio q. The circles and the arrow are the CO-rich early-type galaxies studied here and crosses are the data of Yun, Reddy, & Condon (2001). As defined in Yun et al., the flux ratio q has a mean value of 2.34 for star-forming galaxies (mostly spirals); the lines at $q = 3.04$ and $q = 1.64$ indicate the IR excess and radio excess boundaries, respectively, at roughly 2.7σ from the mean.

that the same is true for the FIR emission in the IRAS 60μm and 100μm bands, Combes et al. (2007) found that the implied star formation efficiencies in the SAURON early-type galaxies are similar to those in normal spirals (Combes et al. 2007). The IRAS data gave no useful morphological information, though, so our analysis provides the validation for this star formation assumption.

6. Summary and open questions

For the majority of the CO-rich early-type galaxies the close agreements between CO, 24μm, and radio continuum morphologies suggest that the bulk of the 24μm emission should be attributed to star formation activity. Radio and FIR flux density ratios are consistent with this interpretation, as are the increased $L_{24\mu m}/L_B$ ratios of the CO-rich over the CO-poor early-type galaxies. The CO, radio, and MIPS data are thus roughly consistent with the UV results implying star formation activity in a few tens of percent of the nearby early-type galaxies. The necessary raw material is present, more or less, and the molecular gas is often being turned into stars. Detailed comparisons with the UV morphologies should be made as well.

Future work should also make more quantitative tests of theoretical and phenomenological models of the star formation process. For example, with a model of the gravitational potential (from the stellar distribution and a mass-to-light ratio) one can test whether the Toomre-type local gravitational instability is consistent with the locations of star formation activity, as discussed by Kawata et al. (2007). The gas-rich early-type galaxies could also provide useful perspective on the workings of the Kennicutt-Schmidt relationship between the star formation rate and the gas surface density. If these models have truly captured some underlying physics of the star formation process they ought to work in the ellipticals and lenticulars as well as in the spirals.

Where the molecular gas came from to begin with is, in general, still an open question. In this regard comparisons of the kinematics of the gas and stars will be useful, as shown in Young et al. (2008), as will correlations between the gas content and the stellar structural and dynamical indicators of the galaxy's history. The gas-to-dust ratios might also help to distinguish whether the molecular gas was acquired from a low metallicity source such as a dwarf galaxy or from a progenitor of roughly solar metallicity.

REFERENCES

Bendo, G. J., Calzetti, D., et al. 2007, MNRAS, 380, 1313

Bendo, G. J., Buckalew, B. A., Dale, D. A., et al. 2006, ApJ, 645, 134

Cappellari, M., 2002, MNRAS, 333, 400

Combes, F., Young, L. M., & Bureau, M. 2007, MNRAS, 377, 1795

Condon, J. J. 1992, ARA&A, 30, 575

de Zeeuw, P. T., Bureau, M., Emsellem, E., et al. 2002, MNRAS, 329, 513

Goudfrooij, P., Hansen, L., et al. 1994, A&AS, 105, 341

Kaneda, H., Onaka, T., Kitayama, T., Okada, Y., & Sakon, I. 2007, PASJ, 59, 107

Kaviraj, S., Schawinski, D., Devriendt, J. E. G., et al. 2007, ApJS, 173, 619

Kawata, D., Cen, R., & Ho, L. C. 2007, ApJ, 669, 232

Kennicutt, R. C. Jr. 1989, ApJ, 344, 685

Lucero, D. M., & Young, L. M. 2007, AJ, 134, 2148

Okuda, T., Kohno, K., Iguchi, S., & Nakanishi, K. 2005, ApJ, 620, 673

Sage, L. J., Welch, G. A., & Young, L. M. 2007, ApJ, 657, 232

Sarzi, M., et al. 2006, MNRAS, 366, 1151

Schawinski, K., Kaviraj, S., Khochfar, S., et al. 2007a, ApJS, 173, 512

Schawinski, K., Thomas, D., Sarzi, M., et al. 2007b, MNRAS, 382, 1415

Shields, J. C. 1991, AJ 102, 1314

Temi, P., Brighenti, F., & Mathews, W. G. 2008, ApJ 672, 244

Temi, P., Brighenti, F., & Mathews, W. G. 2007, ApJ 660 1215

Welch, G. A., & Sage, L. J. 2003, ApJ, 584, 260

Young, L. M. 2002, AJ 124, 788

Young, L. M. 2005, ApJ 634, 258

Young, L. M., Bureau, M., & Cappellari, M. 2008, ApJ, in press

Yun, M. S., Reddy, N. A., & Condon, J. J. 2001, ApJ, 554, 803